



Nitrous Oxide from Agricultural Sources: Potential Role in Greenhouse Gas Emission Reduction and Ozone Recovery

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Summary

Gases other than carbon dioxide accounted for nearly 15% of U.S. greenhouse gas emissions in 2007, yet there has been minimal discussion of these other greenhouse gases in climate and energy legislative initiatives. Reducing emissions from non-carbon dioxide greenhouse gases, such as nitrous oxide (N₂O), could deliver short-term climate change mitigation results as part of a comprehensive policy approach to combat climate change.

Nitrous oxide is 298 times more potent than carbon dioxide in its ability to affect climate change; and moreover, results of a recent scientific study indicate that nitrous oxide is currently the leading ozone-depleting substance being emitted. Thus, legislation to restrict nitrous oxide emissions could contribute to both climate change protection and ozone recovery.

The primary human source of nitrous oxide is agricultural soil management, which accounted for two-thirds of the N₂O emissions reported in 2007 (approximately 208 million metric tons CO₂ equivalent). One proposed strategy to lower N₂O emissions is more efficient application of synthetic fertilizers. However, further analysis is needed to determine the economic feasibility of this approach as well as techniques to measure and monitor the adoption rate and impact of N₂O emission reduction practices for agricultural soil management.

As Congress considers legislation that would limit greenhouse gas emissions (both H.R. 2454 and S. 1733 would require that greenhouse gas emissions be reduced by 83% in 2050), among the issues being discussed is how to address emissions of non-CO₂ greenhouse gases. Whether such emissions should be subject to direct regulation, what role EPA should play using its existing Clean Air Act authority, whether the sources of N₂O should be included among the covered entities of a cap-and-trade system, whether N₂O reductions should be considered offsets to be purchased by the covered entities of a cap-and-trade system, and what role USDA should play in any N₂O reduction scheme are among the issues being discussed. How these issues are resolved will have important implications for agriculture, which has taken a keen interest in climate change legislation.

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Introduction

Policymakers are dedicating considerable attention to climate change mitigation, primarily discussing options for carbon dioxide (CO₂) emission reduction.¹ Less frequently addressed in proposed legislation is emission reduction for non-CO₂ greenhouse gases, such as nitrous oxide (N₂O). However, N₂O reduction efforts have the potential to mitigate climate change. Moreover, N₂O emission sources may be regulated under the existing Clean Air Act as a class I or class II ozone-depleting substance at the discretion of the Environmental Protection Agency (EPA) Administrator. No new legislation needs to be passed to regulate N₂O for climate protection and ozone recovery.

The five non-CO₂ greenhouse gases regularly monitored but not entirely regulated by EPA (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) accounted for nearly 15% of U.S. greenhouse gas (GHG) emissions in 2007, as measured by total tons of CO₂ equivalent.² Nitrous oxide—the third-most abundant greenhouse gas—was responsible for roughly 4% of total U.S. GHG emissions in 2007 by weight. Although they comprise a smaller portion of GHG emissions, non-CO₂ greenhouse gases, including N₂O, are more potent than CO₂. The gases identified above are 25 to 22,800 times more effective than an equivalent weight of CO₂ at trapping heat in the atmosphere, with N₂O being 298 times more potent by weight.³

In addition to being one cause of climate change, N₂O is an ozone-depleting substance (ODS).⁴ Indeed, scientific analysis suggests that N₂O is now the leading ODS being emitted, as emissions of other substances have been reduced significantly owing to regulations enacted in the late 1980s, in the Montreal Protocol on Substances that Deplete the Ozone Layer.⁵ N₂O emission reduction could thus play a compelling role in recovery of the ozone layer as well as in climate change remediation.

The agriculture sector is the primary anthropogenic source of nitrous oxide.⁶ The bulk of U.S. N₂O emissions stem from fertilizing agricultural soils for crop production. Strategies or

¹ For more information on CO₂ emission reduction techniques, see CRS Report RL33801, *Carbon Capture and Sequestration (CCS)*, by Peter Folger. For more information on legislative proposals to address climate change and regulation of greenhouse gases under the Clean Air Act, see CRS Report R40556, *Market-Based Greenhouse Gas Control: Selected Proposals in the 111th Congress*, by Jonathan L. Ramseur, Larry Parker, and Brent D. Yacobucci; and CRS Report R40585, *Climate Change: Potential Regulation of Stationary Greenhouse Gas Sources Under the Clean Air Act*, by Larry Parker and James E. McCarthy.

² U.S. Environmental Protection Agency, *2009 U.S. Greenhouse Gas Inventory Report*, EPA 430-R-09-004, April 2009, <http://epa.gov/climatechange/emissions/usinventoryreport.html>.

³ The potency of a greenhouse gas is described by its global warming potential (GWP), an estimate of how much a greenhouse gas affects climate change over a quantity of time relative to CO₂, which has a GWP value of 1. Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis* (2007), p. 212.

⁴ An ozone-depleting substance is a compound that contributes to stratospheric ozone depletion by releasing chlorine or bromine atoms into the atmosphere when broken down, leading to the destruction of ozone, a substance necessary to prevent harmful UVB rays from reaching Earth.

⁵ The Montreal Protocol is an international treaty crafted to protect the stratospheric ozone layer by gradually eliminating a number of ozone-depleting substances.

⁶ Also in the agriculture sector, animal digestive systems and manure management account for a large portion of U.S. methane emissions. The Intergovernmental Panel on Climate Change (IPCC) assigns nitrous oxide and methane a global warming potential of 298 and 25, respectively.

technologies designated for N₂O emission reduction are limited.⁷ This is partly due to the dispersed nature of N₂O emission sources.

In the agriculture sector, the majority of N₂O is released as a consequence of specific nitrogen cycle processes (nitrification and denitrification) when large amounts of synthetic nitrogen fertilizers are used for crop production. More efficient application of synthetic fertilizers (e.g., precision agriculture, nitrogen inhibitors, nitrogen sensors, controlled-release fertilizer products) is one way to reduce excess amounts of nitrogen available for bacterial processing and eventual release to the atmosphere as N₂O. High costs and difficulty in measuring these products' efficacy, among other deterrents, have hampered widespread adoption of practices to reduce N₂O emissions.

This report focuses on the contributions of N₂O to climate change and ozone depletion. Policy options for N₂O emission reduction, sources of N₂O, and federal support to lower N₂O emissions are discussed.

Nitrous Oxide: A Primer

Nitrous oxide (N₂O), familiar to some as “laughing gas,” contributes to climate change and ozone depletion. Once released, N₂O lingers in the atmosphere for decades (its atmospheric lifetime is approximately 114 years) and is 298 times more effective at trapping heat in the atmosphere over a 100-year time frame than carbon dioxide (CO₂).⁸ N₂O emission quantity estimates have remained fairly constant over the last few years, hovering around 312 million metric tons carbon dioxide equivalent (CO₂e). See **Table 1**.

Table 1. U.S. Greenhouse Gas Emissions
(million metric tons CO₂e)

Gas / Source	2005	2006	2007	Avg. Contribution ^a
Carbon dioxide (CO ₂)	6,090.8	6,014.9	6,103.4	85%
Methane (CH ₄)	561.7	582.0	585.3	8%
Nitrous oxide (N ₂ O)	315.9	312.1	311.9	4%
Hydrofluorocarbons (HFCs)	116.1	119.1	125.5	1.7%
Perfluorocarbons (PFCs)	6.2	6.0	7.5	<1%
Sulfur hexafluoride (SF ₆)	17.9	17.0	16.5	<1%
Total	7,108.6	7,051.1	7,150.1	

Source: Environmental Protection Agency, 2009 U.S. Greenhouse Gas Inventory Report.

a. Average contribution to total U.S. greenhouse gas inventory based on data provided for 2005 to 2007.

⁷ Strategies and technologies for N₂O emission reduction are limited in comparison to resources expended for methane capture. Methane capture technologies, as well as financial and technical support, for point sources have been available for decades. For more information on methane capture, see CRS Report R40813, *Methane Capture: Options for Greenhouse Gas Emission Reduction*, by Kelsi Braemort et al.

⁸ S. Solomon, D. Qin, and M. Manning et al., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth, IPCC, IPCC WG1 AR4 Report*. New York, NY, 2007. <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>. The IPCC assigned N₂O a global warming potential of 298 over a 100-year time horizon.

Sources of N₂O Emissions

Nitrous oxide is emitted from anthropogenic (manmade) and natural sources. Oceans and natural vegetation are the major natural sources of N₂O. Agricultural soil management (e.g., fertilization, application of manure to soils, drainage and cultivation of organic soils) is responsible for two-thirds of anthropogenic U.S. N₂O emissions.⁹ In 2007, N₂O emissions from agricultural soil management totaled more than 200 million metric tons of CO₂e.¹⁰ Other anthropogenic sources of N₂O are combustion by mobile sources (cars, trucks, etc.), nitric acid production, and manure management.¹¹

Figure 1 depicts the origination and passage of nitrogen (N) that leads to N₂O emissions from agricultural soil management. The amount of N₂O emitted from cropland soils largely depends on the amount of nitrogen applied to a crop, weather, and soil conditions. Corn and soybean crops emit the largest amounts of N₂O, respectively, due to vast planting areas, plentiful synthetic nitrogen fertilizer applications, and, in the case of soybeans, high nitrogen fixation rates (**Figure 2**).¹²

The Nitrogen Cycle

Comprehension of the nitrogen cycle (**Figure 3**) is beneficial when crafting policy to reduce N₂O emissions from anthropogenic sources. Nitrogen, an essential element required by organisms to grow, is found throughout the atmosphere in various forms. The nitrogen cycle portrays the routes in which nitrogen moves through the soil and atmosphere in both organic and inorganic form. Certain processes within the nitrogen cycle convert the nitrogen into a form that can be taken up by plants. Four of the major processes are:

- nitrogen fixation—conversion of nitrogen gas (N₂) to a plant-available form;
- nitrogen mineralization—conversion of organic nitrogen to ammonia (NH₃);
- nitrification—conversion of ammonia (NH₃) to nitrate (NO₃⁻) via oxidation (that is, by being combined with oxygen); and
- denitrification—conversion of nitrates back to nitrogen gas.

Nitrous oxide is a byproduct of nitrification and denitrification. Both processes occur naturally. Excess application of nitrogen fertilizer can lead to increased nitrification, which can cause nitrate to leach into groundwater or surface runoff (in turn, this causes eutrophication, which can damage aquatic environments).

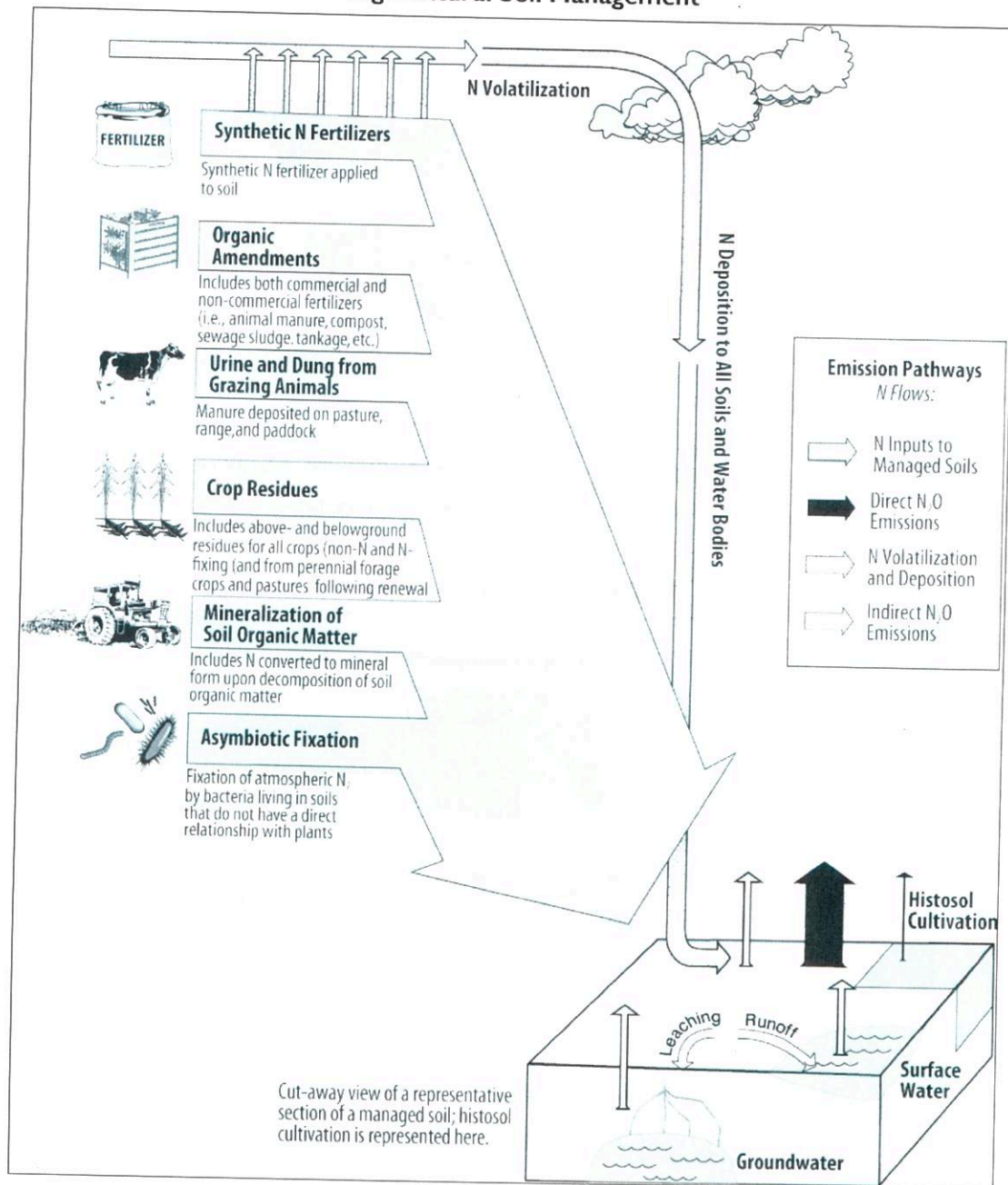
⁹ Agricultural soil management includes practices that add to, or create an environment conducive to the release of, mineral nitrogen (N).

¹⁰ U.S. Environmental Protection Agency, *2009 U.S. Greenhouse Gas Inventory Report*, EPA 430-R-09-004, April 2009, <http://epa.gov/climatechange/emissions/usinventoryreport.html>.

¹¹ Mobile (fuel) combustion leads to N₂O being emitted as a byproduct. N₂O is released as a byproduct during the oxidation of ammonia for production of nitric acid, a primary component of synthetic fertilizers and some explosives. N₂O emissions are generally released in large amounts from dry manure handling systems (e.g., pasture, solid storage).

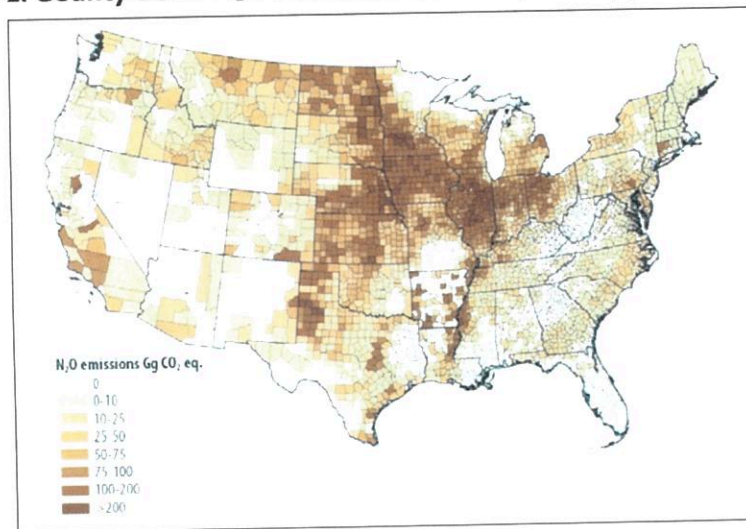
¹² U.S. Department of Agriculture, *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2005*, Technical Bulletin No. 1921, 2008, http://www.usda.gov/oce/global_change/AFGGInventory1990_2005.htm. Nitrogen fixation is the conversion of nitrogen gas to ammonia.

Figure 1. Sources and Pathways of Nitrogen (N) Resulting in N₂O Emissions from Agricultural Soil Management



Source: U.S. Environmental Protection Agency, 2009 U.S. Greenhouse Gas Inventory Report, EPA 430-R-09-004, Chapter 6, April 2009. Adapted by CRS.

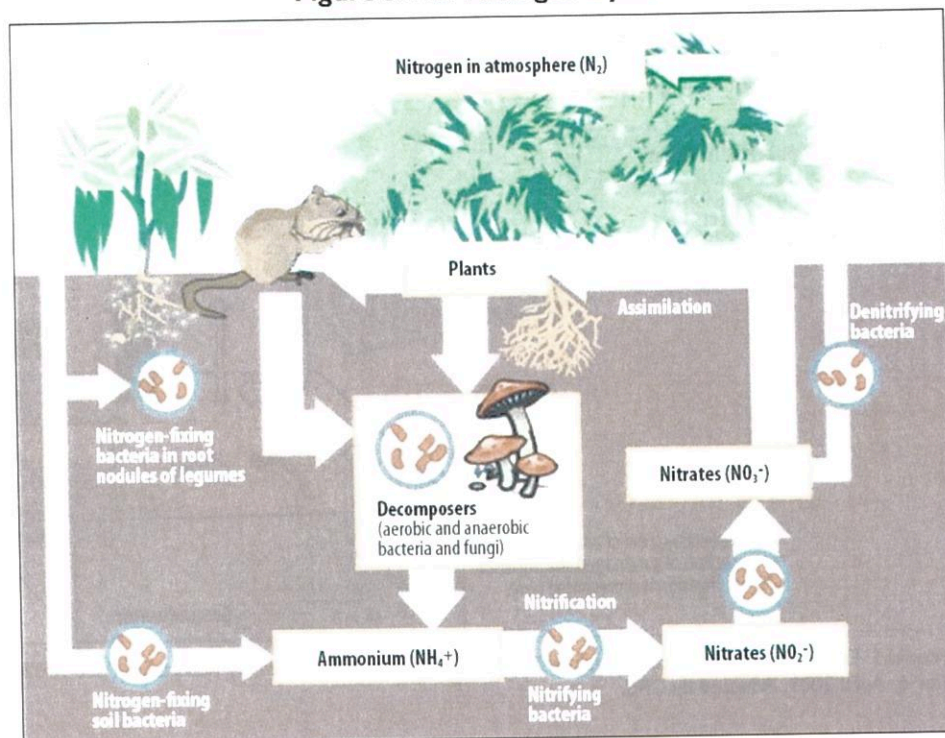
Figure 2. County-Level N₂O Emissions from Major Cropped Soils in 2005



Source: USDA, U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2005. Adapted by CRS.

Notes: 1 Gigagram (Gg) is equivalent to 1,000 metric tons. Major crops are defined as corn, soybean, wheat, hay, sorghum, and cotton.

Figure 3. The Nitrogen Cycle



Source: EPA. Adapted by CRS

Opportunities and Challenges for Nitrous Oxide Emission Reduction

N₂O emission mitigation options are available for agricultural soil management and nitric acid production. Nitric acid is a chemical compound used to make synthetic fertilizers. N₂O abatement options for nitric acid production include a high-temperature catalytic reduction method, a low-temperature catalytic reduction method, and nonselective catalytic reduction.¹³ The estimated reduction efficiencies (the percentage reduction achieved with adoption of a mitigation option) are 90%, 95%, and 85%, respectively.

Agricultural soil management mitigation options recommended by researchers and technology transfer specialists to discourage excess application of nitrogen fertilizers and soil disturbance (Table 2) are not generally being practiced. Fertilizer and soil best-management practices aim to provide the crop with the nutrient and soil conditions necessary for crop production, and prevent nutrient and soil loss from the crop field (e.g., erosion, leaching).¹⁴ Some may consider less money spent towards fertilizer use an economic incentive for agricultural producers.¹⁵ Others may be concerned to ensure that crop yields meet expected feed, fiber, and fuel mandates (e.g., for corn ethanol), which may be difficult to attain with less fertilizer use.¹⁶ Monitoring reduced nitrogen fertilization applications on a large scale for climate change mitigation purposes may be difficult; it is not clear how such a program could be managed at a national level.¹⁷ Enforcement options could include voluntary verification, third-party verifiers, or government intervention.

Reporting N₂O emissions from agricultural soil management was not included in the Final Mandatory Reporting of Greenhouse Gases Rule issued by EPA on September 22, 2009.¹⁸ EPA's reasoning behind this decision was that no low-cost or simple direct N₂O measurement methods exist. Additionally, EPA released a proposed rule requiring new or modified facilities that could trigger Prevention of Significant Deterioration (PSD) permitting requirements to apply for a revision to their operating permits to incorporate the best available control technologies and energy efficiency measures to minimize GHG emissions.¹⁹

¹³ U.S. Environmental Protection Agency, *Global Mitigation of Non-CO₂ Greenhouse Gases*, EPA-430-06-005, 2006. Catalytic reduction methods use a catalyst to reduce nitrous oxides in exhaust gas at varying temperatures.

¹⁴ C. S. Snyder, *Fertilizer Nitrogen BMPs to Limit Losses That Contribute to Global Warming*, International Plant Nutrition Institute, Ref. # 08057, June 2008, <http://www.ipni.net/ipniweb/portal.nsf/0/6D54ABC2C92D9AFA8525749B0074FF59>.

¹⁵ According to the Government Accountability Office, natural gas is the highest-priced factor when producing nitrogen fertilizer. Thus, natural gas prices impact nitrogen fertilizer costs. U.S. General Accounting Office, *Natural Gas: Domestic Nitrogen Fertilizer Production Depends on Natural Gas Availability and Prices*, GAO-03-1148, September 2003, <http://www.gao.gov/new.items/d031148.pdf>.

¹⁶ For example, the Renewable Fuel Standard (RFS) is a provision established by the Energy Policy Act of 2005 requiring gasoline to contain a minimum amount of fuel produced from renewable biomass (including corn). For more information on the RFS, see CRS Report R40155, *Selected Issues Related to an Expansion of the Renewable Fuel Standard (RFS)*, by Brent D. Yacobucci and Randy Schnepf.

¹⁷ For more information on monitoring carbon in agriculture, see CRS Report RS22964, *Measuring and Monitoring Carbon in the Agricultural and Forestry Sectors*, by Ross W. Gorte and Renée Johnson.

¹⁸ For more information on the agricultural implications of the Mandatory Reporting of Greenhouse Gases Rule, see CRS Report RL32948, *Air Quality Issues and Animal Agriculture: A Primer*, by Claudia Copeland.

¹⁹ For more information on the proposed PSD rule, see CRS Report R40585, *Climate Change: Potential Regulation of Stationary Greenhouse Gas Sources Under the Clean Air Act*, by Larry Parker and James E. McCarthy; and EPA, (continued...)

Table 2. Select N₂O Mitigation Alternatives for Agricultural Soil Management

Mitigation Alternative	Description
Split fertilization	Application of same amount of nitrogen fertilizer as in baseline but divided into three smaller increments during crop uptake period to better match nitrogen application with crop demand and reduce nitrogen availability for leaching, nitrification, denitrification, and volatilization.
Simple fertilization reduction (10%, 20%, or 30%)	Reduction of nitrogen-based fertilizer from one-time baseline application of 10%, 20%, or 30%.
Nitrification inhibitor	Reduces conversion of ammonium to NO ₃ ⁻ , which slows the immediate availability of nitrate (nitrate is water soluble). The inhibition of nitrification reduces nitrogen loss and increases overall plant uptake.
No-till	Conversion from conventional tillage to no-till, where soils are disturbed less and more crop residue is retained.

Source: EPA, *Global Mitigation of Non-CO₂ Greenhouse Gases*, http://www.epa.gov/climatechange/economics/downloads/GM_SectionV_Agriculture.pdf.

Federal Support for Nitrous Oxide Emission Reduction

USDA provides some financial and technical assistance for nutrient management through its conservation programs.²⁰ Moreover, USDA's Agricultural Research Service (ARS) is studying the relationship between agricultural management practices and nitrous oxide emissions.²¹

In addition to the agriculture sector, work is being done in the transportation sector to reduce N₂O emissions. Mobile combustion was responsible for nearly 10% of N₂O emissions reported in 2007.²² One N₂O emission reduction initiative, proposed by EPA and the Department of Transportation, is to cap tailpipe N₂O emissions at 0.010 grams per mile as part of a wider effort to reduce greenhouse gas emissions and improve fuel economy in tandem, via a CO₂ emission standard for light-duty vehicles.²³ EPA has allocated financial resources to quantify N₂O emissions for the greenhouse gas inventory (e.g., DAYCENT model).²⁴

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Proposed Rule: Prevention of Significant Deterioration and Title V Greenhouse Gas Tailoring Rule, 2009, <http://www.epa.gov/NSR/fs20090930action.html>.

²⁰ For more information on agricultural conservation programs, see CRS Report R40763, *Agricultural Conservation: A Guide to Programs*, by Megan Stubbs. For more information on technical assistance for nutrient management, see USDA, Natural Resources Conservation Service, *Conservation Practice Standard—Nutrient Management Code 590*, August 2006, <ftp://ftp-fc.sc.egov.usda.gov/NHQ/practice-standards/standards/590.pdf>.

²¹ For more information on the efforts underway at ARS, visit the Air Quality of Agricultural Systems Research Unit website at http://www.ars.usda.gov/main/site_main.htm?modecode=36-25-15-15, or the Air Quality National Program website at http://www.ars.usda.gov/research/programs/programs.htm?NP_CODE=203.

²² U.S. Environmental Protection Agency, *2009 U.S. Greenhouse Gas Inventory Report*, EPA 430-R-09-004, April 2009, <http://epa.gov/climatechange/emissions/usinventoryreport.html>.

²³ U.S. Environmental Protection Agency, *EPA and NHTSA Propose Historic National Program to Reduce Greenhouse Gases and Improve Fuel Economy for Cars and Trucks*, EPA-420-F-09-047, September 2009, (continued...)

Policy Options for Nitrous Oxide Emission Reduction

Congress has begun to investigate the reduction of non-CO₂ greenhouse gas emissions, including N₂O emissions, as one strategy to mitigate climate change. Some contend that N₂O emissions reduction could serve as a short-term response in the larger, long-term scheme of mitigation and adaptation efforts.²⁵ It may be viewed as a short-term response because N₂O emissions make up a small amount of the GHG inventory compared to CO₂ emissions. Any substantial approach to mitigate climate change is likely at some point to have to address sources that emit CO₂.

Congress could approach N₂O emissions reduction as part of a comprehensive GHG emission strategy offering economically attractive abatement alternatives to discourage actions leading to climate change. For example, a cap or fee on N₂O emissions could spur innovative methods for agricultural producers to limit excess synthetic fertilizer application. Congress could also examine the tools necessary to identify N₂O emission abatement options, assess their cost, and determine their economic impact for full incorporation into climate change legislation.

Besides mitigating climate change, reducing N₂O emissions could lead to ozone recovery. Congress could explore the co-benefits that may arise from restricting N₂O emissions for climate change purposes. N₂O is not regulated as an ODS under the Clean Air Act, Title VI, Stratospheric Ozone Protection (as guided by the Montreal Protocol). As emissions of other ODSs (e.g., chlorofluorocarbon-11, halon-1211) have declined due to regulation, N₂O has emerged as the dominant ODS emission.²⁶ The first-ever published ozone depletion potential (ODP) value assigned to N₂O, 0.017, is less than the ODP value of 1.0 for the reference gas chlorofluorocarbon 11 (CFC-11). While some may not see a cause for alarm based on the ODP value alone, the quantity of N₂O emissions and its potency as a GHG can lead to serious harm (see **Table 1**).

The ODP value for N₂O does not allow for its mandatory inclusion as a class I substance for regulation under the Clean Air Act.²⁷ However, N₂O could be listed as a class II substance at the direction of the EPA Administrator or regulated under Section 615 of the act.²⁸ Class I substances have an ODP of 0.2 or more and are more harmful to stratospheric ozone molecules than Class II substances, which have an ODP of less than 0.2.

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<http://www.epa.gov/otaq/climate/regulations/420f09047.htm>.

²⁴ EPA uses the DAYCENT ecosystem model for the U.S. greenhouse gas inventory “to estimate direct N₂O emissions from mineral cropland soils that are managed for production of major crops—specifically corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton.”

²⁵ Shilpa Rao and Keywan Riahi, “The Role of Non-CO₂ Greenhouse Gases in Climate Change Mitigation: Long-Term Scenarios for the 21st Century,” *Energy Journal*, vol. 27 (2006), pp. 1-26; Mario Molina, Durwood Zaelke, and K. Madhava Sarma et al., “Reducing Abrupt Climate Change Risk Using the Montreal Protocol and Other Regulatory Actions to Complement Cuts in CO₂ Emissions,” *Proceedings of the National Academy of Sciences of the United States of America*, October 12, 2009.

²⁶ A. R. Ravishankara, John S. Daniel, and Robert W. Portmann, “Nitrous Oxide (N₂O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century,” *Science Express*, August 27, 2009.

²⁷ 42 U.S.C. § 7671a. The EPA Administrator may add to the list of class I substances any substances that the Administrator determines as having an ozone depletion potential of 0.2 or greater.

²⁸ 42 U.S.C. § 7671n. The EPA Administrator has the authority to promptly promulgate regulations respecting the control of an ODS by submitting notice of the proposal and promulgation of such regulation to the Congress.

With or without ODP substance listing, Congress may find it useful to incorporate the ozone depletion impacts of N₂O into its climate change policy proposals both to reduce greenhouse gas emissions and to further ozone recovery achievements. Classifying N₂O emission reduction as an eligible offset type, including N₂O as a covered entity within a cap-and-trade program, or directing EPA to use existing authority under the Clean Air Act to regulate N₂O are other available options to reduce N₂O emissions for ozone or climate protection. Any option chosen to reduce N₂O emissions will more than likely require an improvement of N₂O estimation, measurement, and reporting methods and possible financial incentives.

Congress could apply lessons learned from previous international agreements that are intended to abolish harmful compounds. The outcomes of the Montreal Protocol, put into action in the late 1980s, may prove useful to Congress in understanding the long-term implications of certain climate change policy options, specifically cap-and-trade. A number of gases were phased out under the Protocol, which allowed for each country to establish a regulatory framework to monitor and reduce ODSs. Certain ozone-depleting substances, such as N₂O, were not included in the Protocol partly because their threat was not perceived as urgent at the time. However, one unintended consequence of the success of the Protocol reducing targeted ODSs is that N₂O has emerged as the leading ODS.

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Desk Statement on Nitrous Oxide Article in *Science*

“Nitrous Oxide (N₂O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century” by A.R. Ravishankara, John S. Daniel and Robert W. Portmann of NOAA

An article published in the journal *Science* today calculates the ozone-depletion potential (ODP) of nitrous oxide (N₂O) for the first time. The article then compares ODP-weighted emissions of N₂O from human activities with emissions of other ozone-depleting substances (ODS). With the exception of N₂O, most ODS such as chlorofluorocarbons (CFCs) are controlled by the international treaty to protect the ozone layer, the Montreal Protocol. CFCs and other fluorinated gases are produced for use in consumer and industrial applications while N₂O emissions come from a variety of sources, including agricultural fertilization and industrial production. Because of large reductions in emissions of other ODS – a result of successful efforts to eliminate production of these chemicals worldwide under the Montreal Protocol – the study concludes that N₂O is now the largest remaining uncontrolled ODS.

Results of this study underscore the complex relationship between ozone depletion and climate change. It has long been understood that N₂O damages ozone in the stratosphere, but because N₂O is also a climate-forcing gas, it is included in the “basket of gases” covered by the Kyoto Protocol, the international treaty addressing climate change. EPA will continue to work with leading scientists to better understand the implications of this study for future policies to protect the world’s atmosphere from both ozone layer depletion and climate change.

Findings and implications of the paper
“Nitrous Oxide (N₂O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century
by A. R. Ravishankara, John S. Daniel, and Robert W. Portmann of NOAA

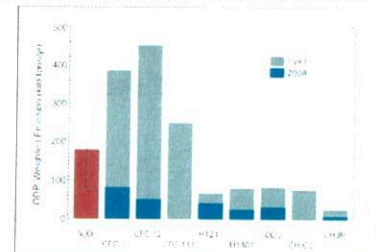
What is known about N₂O and nitrogen oxide-driven ozone layer depletion?

1. Based on the seminal work of Crutzen and Johnston, it has been known for nearly 40 years that nitrogen oxides cause ozone reductions and are involved in maintaining natural levels of ozone. Emission of nitrogen oxides from supersonic transport (aircraft) and the ensuing ozone depletion was the very first reason for the concern about anthropogenic impacts on the ozone layer.
2. It has been known for over 30 years that nitrous oxide (N₂O) is the primary source of nitrogen oxides in the stratosphere.
3. It is known that a significant fraction of the N₂O emissions are due to human activities such as agricultural fertilization and industrial production. The preindustrial level of N₂O was about 270 parts per billion (ppb), and the current level is roughly 325 ppb. Its concentration in the atmosphere continues to increase.
4. Many studies have examined what happens to the stratospheric ozone layer if nitrous oxide emissions are altered.

What is new from this study?

1. The study calculates the ozone depletion potential (ODP)—a relative measure of stratospheric ozone depleted by a unit mass emission of a gas relative to that for emission of a unit mass of chlorofluorocarbon-11—of N₂O to be roughly 0.017. This positive number is comparable to the ODPs of some of the HCFCs and implies that N₂O is an ozone-depleting gas. Although the literature widely supports that N₂O destroys ozone, to our knowledge, this is the first time N₂O is suggested to be an ozone-depleting substance in the way that other gases, already regulated under the Montreal Protocol, are.
2. More importantly, the study compares the ODP-weighted anthropogenic emissions of nitrous oxide with those of CFCs and other ozone-depleting substances. It shows that N₂O emissions in these terms were the fourth largest even at the height of the CFC emissions in 1987 prior to the Montreal Protocol. It also shows that N₂O is now, and is expected to be for the next century, the largest ozone depletion gas emission if the anthropogenic N₂O emissions are unabated.
3. The study compares the contribution of N₂O emissions to various other ODS controls that are envisaged and notes the large magnitude of N₂O's contribution to ozone depletion compared to those from other considered measures.
4. N₂O is also a greenhouse gas. The study notes that there would be climate AND ozone layer benefits to reductions in N₂O emissions— a “win-win” for both ozone and climate.

Bottom line: the dots were all there, but this study connected the dots to show that emissions of nitrous oxide are the most harmful to the ozone layer of all the substances being emitted today-- and will remain so for the 21st century under current policies.



Two important points that could cause confusions: (a) Even though N₂O depletes the global ozone layer, its impact on the ozone hole (the annual late-winter-springtime ozone loss in the Austral stratosphere) is negligible! This difference between CFCs and N₂O comes about because of interesting chemistry differences. This could be a major point of confusion to the public and the press. (b) Currently, stratospheric ozone depletion is dominated by ODSs already regulated by the Montreal Protocol, which have accumulated to large concentrations

Who should care about these results?

1. The general public, who should know that ozone layer depletion has been occurring ever since industrialization.
2. Policy makers who deal with ozone layer depletion policy and climate change policy. This includes many US agencies, US negotiators, US EPA, USDA, State Dept., etc. It also includes international institutions such the UNEP and WMO.
3. Scientists—because many assumptions about the dates for when the ozone layer depletion started, when the ozone layer will recover, and many other issues will have to be reexamined.

Some sensitivities (ones that we can think of now):

1. USDA may be very sensitive to this finding since the predominant sources of man-made N₂O emissions are from agricultural practices.
2. US EPA will be sensitive to this finding since it may have to declare N₂O an ozone-depleting gas and may have to regulate its emissions.
3. Many Nations will be sensitive to this because all have signed the Montreal Protocol and, now, an agriculture-related emission may have to be dealt with. It may also affect many choices in reductions that the countries have agreed to make and are likely to agree to make, for example the HFC phase down under the Montreal Protocol.

Policy Implications:

1. As an ozone-depleting substance N₂O may have to be considered under the Montreal Protocol and thereby require an amendment to the protocol. As a more important gas to climate change currently than the collection of HFCs, regulation of N₂O under both a climate agreement and the Montreal Protocol could pose challenges to negotiations.
2. Given the introduction of another ozone-depleting substance to the mix, nations may want to reexamine their strategies for phasing out other ODSs and their substitutes.
3. The increased potential regulation of many greenhouse gases under different treaties could call into question the basket of gases approach for climate gases.

Nitrous Oxide (N₂O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century

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Key Points of Presentation

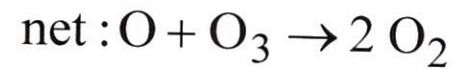
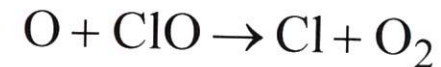
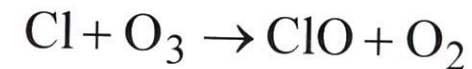
1. Fact: NO_x from N_2O leads to ozone depletion; N_2O is not regulated under the Montreal Protocol.
2. In this paper: We have treated N_2O like any other ozone-depleting substance (CFCs, Halons, methyl bromide,...), and calculated its Ozone Depletion Potential (ODP).
3. In this paper: We used that ODP to compare the ODP-weighted emissions of *anthropogenic* N_2O to the ODP-weighted anthropogenic emissions of other ozone-depleting substances.
4. Finding: Anthropogenic N_2O is now the largest manmade ozone-depleting gas emission (a recent development owing to the successful abatement of CFCs and other ODSs under the Montreal Protocol!), and it will remain so for the next century if anthropogenic emissions of N_2O are unabated.

What we know: Chlorine catalyzes Ozone destruction

Gas phase homogeneous catalytic reactions that can destroy millions of times more ozone- small amounts can cause a big change



CFCs
(chlorofluorocarbons)



Molina and Rowland

Findings from 2002 and 2006 SAP of UNEP/WMO:

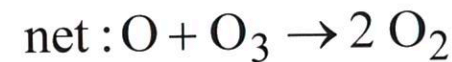
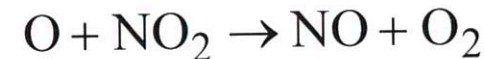
- The Montreal Protocol is a success!
- The chlorine (and bromine) containing ODSs are decreasing in the atmosphere
- The ozone layer is expected to recover
- It is showing signs of recovery

What we know: NO_x also catalyzes ozone destruction



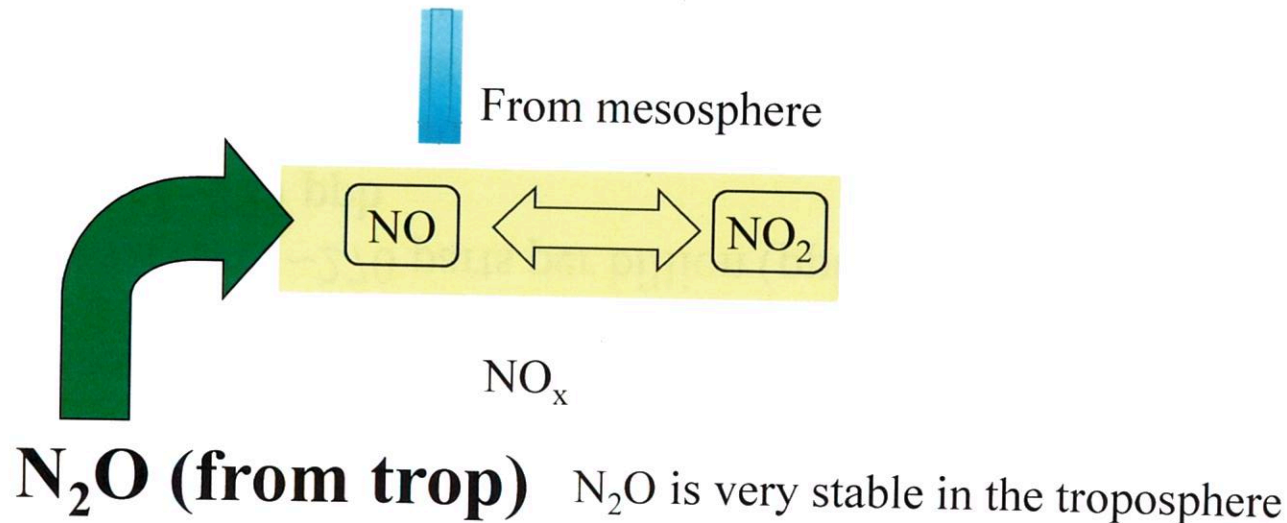
SSTs

NO/NO_2



- Additional catalytic cycles are also involved in O_3 destruction
- The NO_x cycle is a major ozone destroyer in the mid- to- upper stratosphere (part of the “natural” cycles?)
- Seminal work of Crutzen and Johnston ~ 40 years ago
 - nitrogen oxides cause ozone reductions.
- Nitrogen oxides from SSTs deplete ozone
 - the very first ozone layer depletion issue.

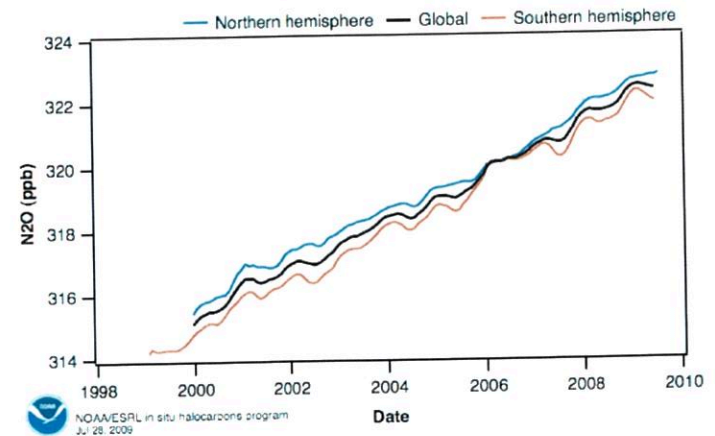
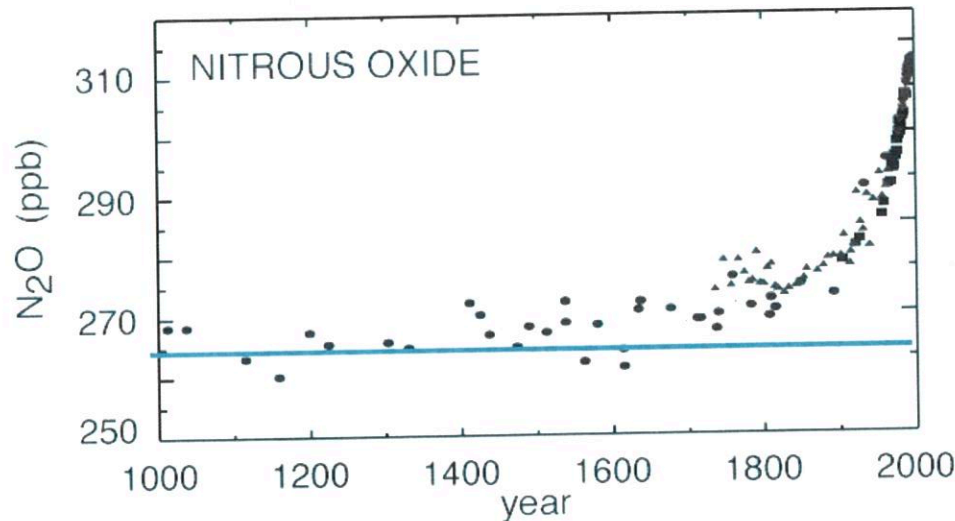
What we know: N_2O is the main source of stratospheric NO_x



- ☐ As N_2O is converted to NO_x in the stratosphere
- ☐ ~10% of N_2O is converted to NO_y (NO_x)
- ☐ N_2O is the largest source of NO_x in the stratosphere

Many studies have examined what happens to the stratospheric ozone layer if nitrous oxide emissions are altered. Conclusion- Increasing N_2O leads to decreased in O_3 .

What we know: A significant part of N_2O emission is of human origin



- Preindustrial level ~270 parts per billion (ppb)
- Current level ~325 ppb
- Concentration continues to increase at roughly 0.25% (of total) per year; i.e., ~1% of anthropogenic component per year.
- All Increases in N_2O is due to anthropogenic activity– looks like other anthropogenic emissions, e.g., CO_2 , CH_4
- Anthropogenic sources: agricultural fertilization, combustion, industrial production, etc.

What we did

Ozone Depletion Potential of N₂O

$$\text{ODP} = \frac{\text{Integrated Ozone depleted by emission of 1 kg of N}_2\text{O}}{\text{Integrated Ozone depleted by emission of 1 kg of CFC-11}}$$

Calculated ODP using Garcia-Solomon model for 2000 conditions

$$\text{ODP of N}_2\text{O} = 0.017$$

This **positive** number for ODP is comparable to those of some of the HCFCs:
HCFC-123 = 0.02; HCFC-124 = 0.022; HCFC-225ca = 0.025; HCFC-225cb = 0.033

N₂O is an ozone-depleting gas!

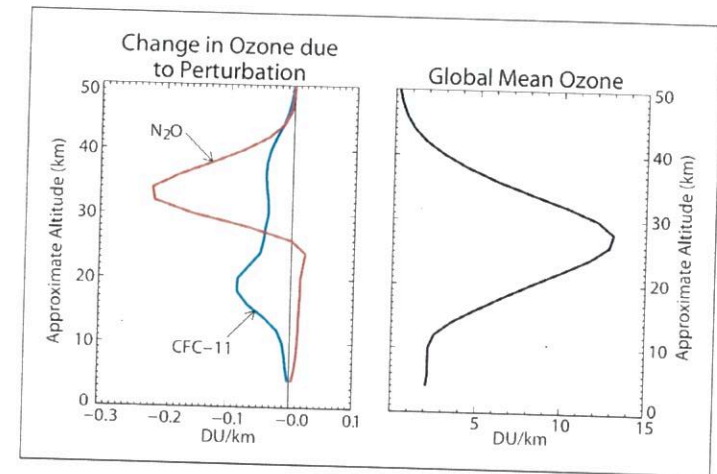
- Previous literature widely supports that N₂O destroys ozone
- To our knowledge, this is the first time N₂O is suggested to be an ozone-depleting substance in the same way that other gases that are already regulated under the Montreal Protocol

A few points about calculated ODP

Calculated ODP is robust

ODPs calculated in this study for CFC-12 is 1.03 and HCFC-22 is 0.06-agree with literature values.

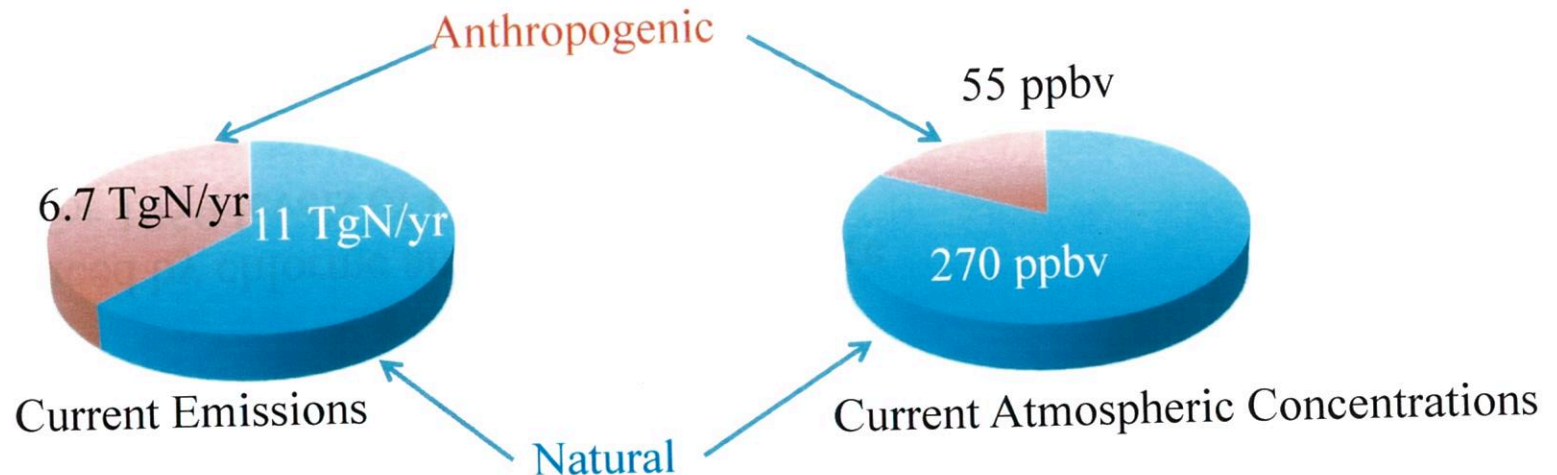
O₃ depletion dominated by NO_x in mid-stratosphere, where 2D models do well



ODP influenced by chlorine amount in stratosphere
- ODP for 1959 levels of ODSs is 0.026

ODP is influenced by amount of sulfate aerosol in the stratosphere
- ODP for volcanic (like Mt. Pinatubo) conditions is 0.009 for 2000 and 0.019 for 1959; i.e., different ODPs for volcanic and non-volcanic periods
But, volcanic periods last only a couple of years

Implications of our findings



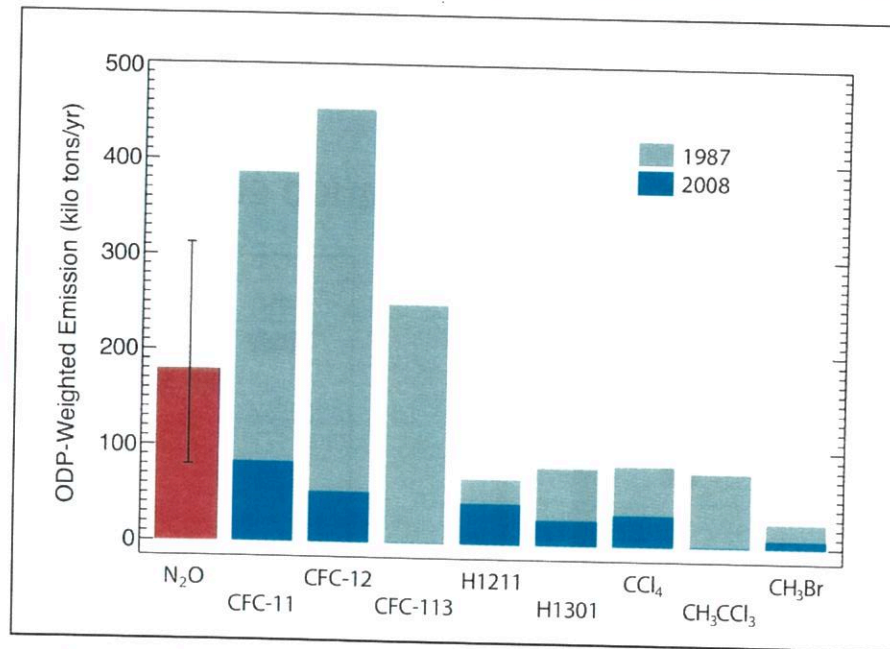
- ◆ Large Natural Emissions
- ◆ Even larger natural concentrations
- ◆ Anthropogenic concentrations growing rapidly

Two Key Points:

- Our discussion is restricted to anthropogenic emissions
 - the ones that are under human control
- N_2O 's ODP is small
 - but its emissions are large

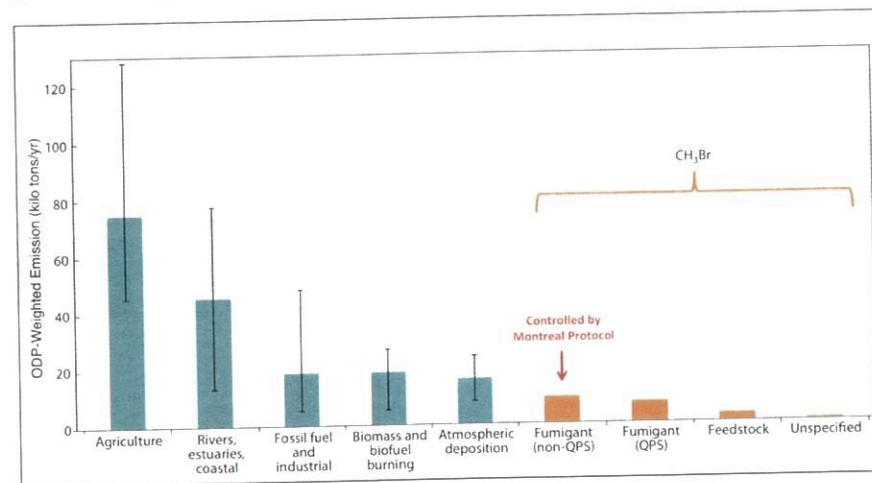
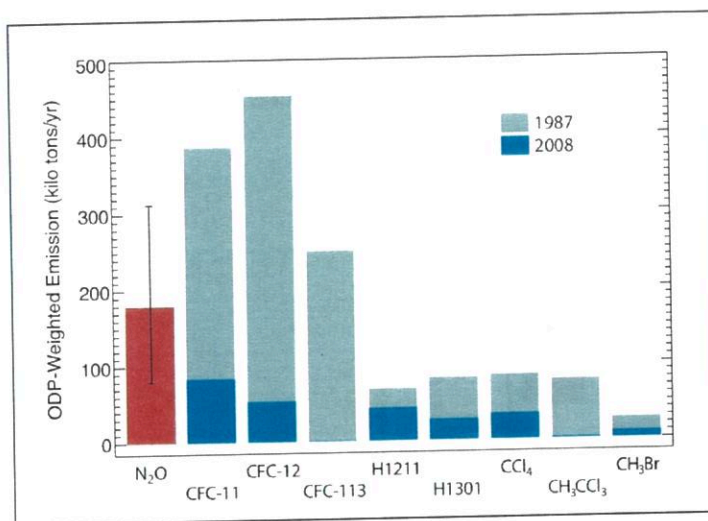
ODP alone does not tell the story

Compare the ODP-weighted anthropogenic N_2O emissions- not ODP- with those of CFCs and other ozone-depleting substances



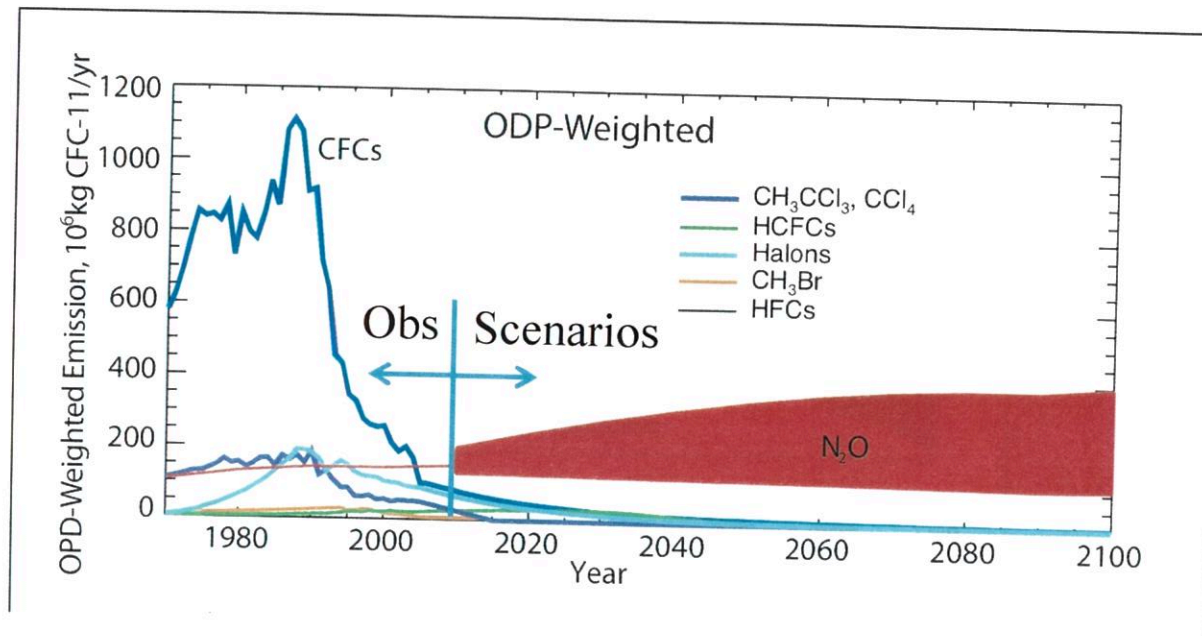
- Anthropogenic ODP-weighted-emissions of N_2O were the **fourth** largest ODS emissions even in 1987, at the height of the CFC emissions prior to the MP.
- Anthropogenic N_2O is now the largest ozone depletion gas emission; it will continue to be so and get even larger in the 21st century if the anthropogenic N_2O emissions are unabated.

How does N₂O stack up against other emissions?



- Compares N₂O emissions contribution with some other ODS control strategies
- N₂O's contribution to ozone depletion is large compared to others when ODP-weighted emissions are used.
- Compare with methyl bromide- an emission related to agricultural and has both natural and anthropogenic origins
- The bank of CFCs is roughly equal to ~15 years of N₂O emissions

N_2O : the dominant ozone depleting substance emitted in the 21st century

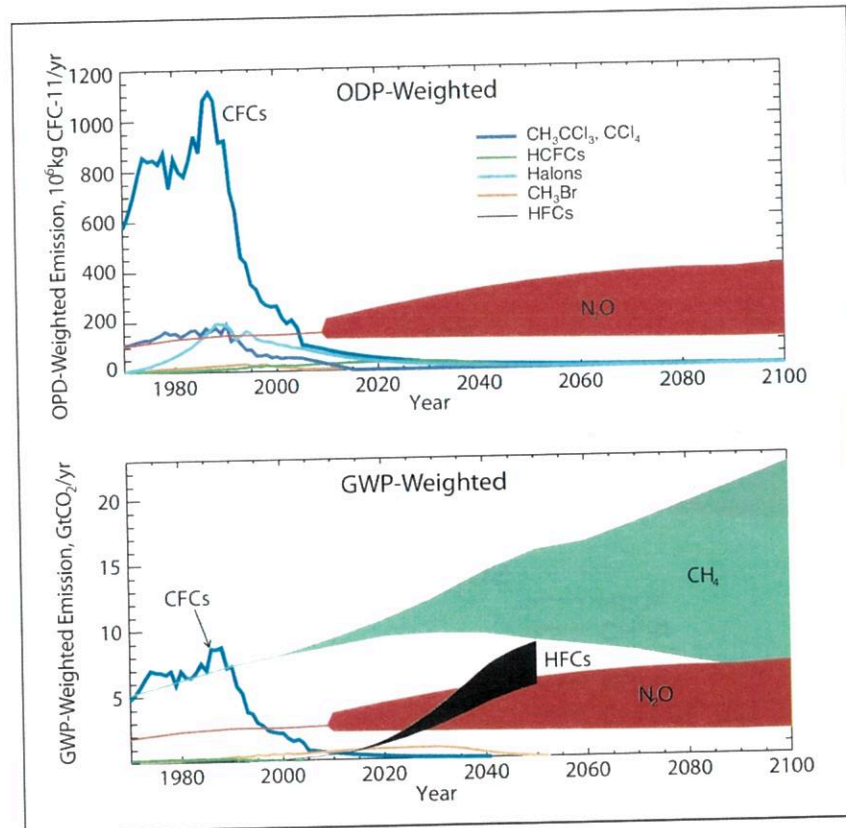


- N_2O is already the dominant ozone depleting substance being emitted today!
- Continued growth in N_2O , combined with decreasing chlorine loading, makes it even more important in the future.
- There are uncertainties in projections of N_2O growth- but even the most optimistic projections shows an increasing N_2O trend.

Climate benefits of reduced N_2O

Ozone
depletion

Climate
Forcing



There would be climate AND ozone layer benefits to reductions in N_2O emissions
— a “win-win” for both ozone and climate.

Differences between current ODSs and N₂O

- Chlorine and bromine containing ODSs induce ozone hole
- N₂O has negligible effect on ozone hole!
- Completely different chemistry- heterogeneous chemistry suppresses effects of N₂O in lower stratosphere and polar winter-spring stratosphere while het chem. enhances effects of chlorine.
- Different responses to volcanoes- chlorine induced ozone depletion increases, N₂O induced Nox effects decrease
- Differences in vertical regions of where these chemicals are active- with its implications to climate change and other changes
- Coupling with cycles different

Other issues

Changes in anthropogenic N_2O emissions will affect:

- (a) the estimated date for the recovery of the ozone layer;
- (b) imply that the use of a single parameter such as Equivalent Effective Stratospheric Chlorine, EESC, to estimate the recovery of the ozone layer should be reevaluated;
- (c) implications for the recovery of the polar ozone hole that might differ from that of global ozone;
- (d) Calls in to question the “baseline” for ozone recovery.

N_2O could be an unintended byproduct of enhanced crop growth for biofuel production or iron fertilization to mitigate CO_2 emissions. Such an enhancement would lead to the unintended ‘indirect’ consequence of ozone layer depletion and increased climate forcing from N_2O produced for alternative fuel used to curb global warming

For history: Ozone depletion by anthropogenic N_2O is roughly the same as that from the original projections for 500 US supersonic transport SSTs.

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Additional Slides

What we know: Others have studied the effect of N_2O increase

Many studies have examined what happens to the stratospheric ozone layer if nitrous oxide emissions are altered

Examples:

- Kinnison et al. (1988)
- Randeniya et al. (2002)
- Chipperfield and Feng (2003)

All indicate that ozone would decrease if N_2O increases

How is N₂O converted to NO_x?

